



Jennings, D., & McGeehan, JP. (1999). A high-efficiency RF transmitter using VCO-derived synthesis: CALLUM. *IEEE Transactions on Microwave Theory and Techniques*, 47(6, Part 1), 715 - 721. <https://doi.org/10.1109/22.769341>

Peer reviewed version

Link to published version (if available):
[10.1109/22.769341](https://doi.org/10.1109/22.769341)

[Link to publication record in Explore Bristol Research](#)
PDF-document

University of Bristol - Explore Bristol Research

General rights

This document is made available in accordance with publisher policies. Please cite only the published version using the reference above. Full terms of use are available:
<http://www.bristol.ac.uk/red/research-policy/pure/user-guides/ebr-terms/>

A High-Efficiency RF Transmitter Using VCO-Derived Synthesis: CALLUM

David J. Jennings and Joseph P. McGeehan

Abstract—The combined analog locked-loop universal modulator (CALLUM) is a radio-frequency (RF) transmitter topology which produces a linear output through the use of nonlinear, but highly efficient, RF power amplifiers. This is achieved through careful phasing of two constant-envelope vectors, each derived from voltage-controlled oscillators. The system up-converts and amplifies a baseband signal within a closed-loop feedback scheme. The optimal CALLUM system requires complex baseband processing, but a simplified version, known as CALLUM2, can be implemented using simple analog circuitry. This paper provides some insight into the behavior of such systems and gives results from an experimental CALLUM2 system in response to a modulating signal compatible with that used in the terrestrial trunked radio standard.

Index Terms—CALLUM, linear modulators, VCO-derived synthesis.

I. INTRODUCTION

THE ever-increasing use of mobile communications equipment has necessitated the use of spectrally efficient modulation schemes such as $\pi/4$ differential quaternary phase-shift keying (DQPSK). Such schemes require a linear transmitter to preserve the trajectory of the complex signal, thereby confining the transmitted power to a well-defined bandwidth and not causing interference in adjacent channels. While reasonable levels of linearity can be achieved from class-A amplifiers, such arrangements are not power efficient and are, therefore, unsuitable for use in portable or handheld equipment. Existing ways of producing linear power-efficient transmitters involve using an amplifier stage of increased efficiency such as class C, and then attempting to linearize the resulting output. Several linearization techniques exist, the most common of which are Cartesian loop, feedforward, and predistortion [1]. A more radical approach to producing a high-efficiency linear transmitter is to use the combined analog locked-loop universal modulator (CALLUM). Unlike other systems, CALLUM offers the potential of ultrahigh DC-to-radio-frequency (RF) power conversion efficiency which, in theory, approaches 100%. Clearly, such a transmitter would find extensive use in handheld battery-operated systems.

The CALLUM system produces a linear high-level RF output signal in the same way as does the linear amplification

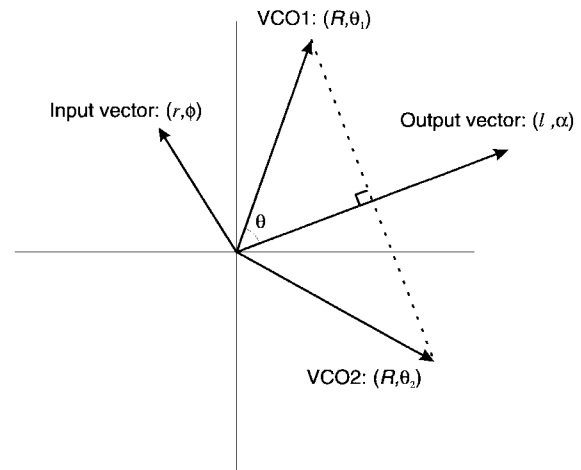


Fig. 1. Input and output vectors on the complex plane.

with nonlinear components (LINC) method proposed by Cox [2]. An arbitrary input signal varying in phase and amplitude is decomposed into two constant-envelope signals, which can each be amplified by grossly nonlinear, but highly efficient, RF power amplifiers (PA's), and then recombined at a high level to synthesize the required phase and amplitude-varying output. Fig. 1 shows the input, synthesized output, and two component vectors. The output vector is always equal to the resultant of the two component vectors; the purpose of any LINC-like system is to control the phase of each component vector such that the output and input vectors are the same. The constant-envelope signals are derived from two voltage-controlled oscillators (VCO's), the phases of which are controlled by the application of suitable control signals.

The original LINC system operated in an open-loop configuration and was sensitive to small gain and phase imbalances in the two component arms [3]. The CALLUM system has a closed-loop topology and can continually correct for such imbalances. It is a complete transmitter scheme that both up-converts and linearly amplifies a baseband signal represented in Cartesian form within a closed-loop system. Due to the closed-loop high-gain nature of this arrangement, the system is inherently narrow-band. The bandwidth of the system is defined by the dominant poles and time delay around the loop, which will eventually cause instability at higher gain levels. Another VCO-derived synthesis method called the vector locked-loop (VLL) [4] operates in a similar manner, but the required signal processing utilizes polar (magnitude and phase) rather than Cartesian signals.

Manuscript received December 1, 1998; revised February 5, 1999. This work was supported by the Engineering and Physical Sciences Research Council. An early version of this paper was presented at the IEEE RAWCON'98, Colorado Springs, CO.

The authors are with the Centre for Communications Research, University of Bristol, University Walk, Bristol BS8 1TR, U.K.

Publisher Item Identifier S 0018-9480(99)04279-9.

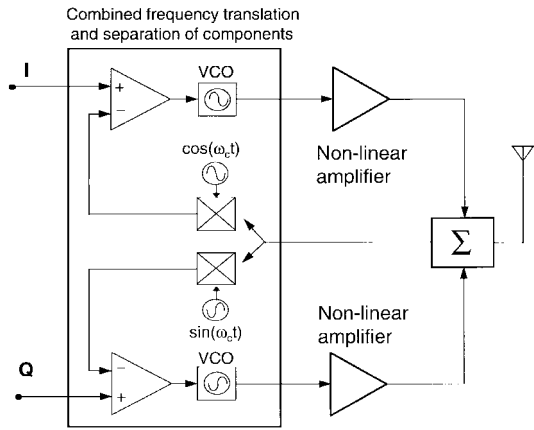


Fig. 2. Topology of the basic CALLUM system proposed in [5].

II. SYSTEM DESCRIPTION

In the generic form of CALLUM, proposed by Bateman [5], the two VCO's are driven with the error signal generated by comparing the input and downconverted Cartesian components (Fig. 2). This system is not stable for all input phases; however, stability can be guaranteed if a sign-switching matrix is employed [6]. Unfortunately, this modified version suffers from discontinuities when the input signal changes from one quadrant of the complex plane to another. As the transition occurs, lock is temporarily lost and the system goes through a reacquisition process. In addition, the dynamic behavior of the system and, in particular, the tracking performance, changes with the input vector. There exists a particular input phase for which system performance is maximized.

To overcome the shortcomings of the CALLUM system, an improved version was subsequently proposed [7], which is stable for all input phases and does not suffer from discontinuities. The resulting system, known as CALLUM1, requires the calculation of several nonlinear functions of the system's variables. The effect of the calculation is to perform continual phase rotation and amplitude normalization such that dynamic performance is optimized. To implement CALLUM1, the VCO's must be excited with control signals which are derived from functions of the baseband input signal and error signal vectors (plus known system constants)

$$\begin{aligned} v_1 &= k\Delta x \left[\frac{-x}{cr\sqrt{4R^2 - r^2}} - \frac{y}{cr^2} \right] \\ &\quad + k\Delta y \left[\frac{x}{cr^2} - \frac{y}{cr\sqrt{4R^2 - r^2}} \right] \\ v_2 &= k\Delta x \left[\frac{x}{cr\sqrt{4R^2 - r^2}} - \frac{y}{cr^2} \right] \\ &\quad + k\Delta y \left[\frac{x}{cr^2} + \frac{y}{cr\sqrt{4R^2 - r^2}} \right] \end{aligned} \quad (1)$$

where x and y are the Cartesian components of the input signal, Δx and Δy are the corresponding error signals, c is the VCO sensitivity, k is the loop gain, r is the input signal envelope, and R is the magnitude of the two VCO vectors. Implementing these equations is not easy; a practical method of generating v_1 and v_2 might be to employ a digital signal processor (DSP) or look-up table (LUT) [8]. This would be

feasible because the bracketed terms of (1) can be generated outside the feedback loop, thus minimizing the effect of time delay on loop stability. However, it should be kept in mind that although the baseband input signal would typically be of the order of 20 kHz, the nonlinear nature of (1) can result in terms that have a bandwidth of many times this figure. For a $\pi/4$ -DQPSK baseband input modulation signal, a tenfold expansion can be expected. The closer to the complex origin that the input signal trajectory passes, the greater the bandwidth expansion. The overall aim of the CALLUM control circuitry is to derive the required VCO control signals to phase the two component vectors correctly, to allow the synthesized output vector to track the input vector. Before lock is achieved, the system must undergo an acquisition process similar to that which occurs in phase-locked loops [9].

One disadvantage of the two-VCO CALLUM system is its inability to remain locked when the input envelope goes through zero, as is the case with a traditional two-tone test. By using three or more VCO's [10], this problem can be overcome, but the cost is increased complexity. To illustrate how the phase of the component vectors are controlled, it is useful to examine the VCO control voltages when synthesizing a two-tone input signal. Fig. 3 shows the VCO control voltages and input signals for a two-tone test with the following parameters: 1) Tone 1: frequency = 1 kHz, amplitude = 1.2 V. 2) Tone 2: frequency = 2 kHz, amplitude = 1.5 V. Since the amplitudes are unequal, the envelope of the combined signal does not fall to zero. Fig. 3 shows that, as the envelope falls, the VCO control voltages have to increase to force the component vectors to assume the desired phase. A single-tone input generates DC control voltages once acquisition has occurred.

It was shown in [7] that when considering small changes in either the phase or amplitude of the input vector from a locked state, the nonlinear system can be approximated by a simple first-order linear relationship with a time constant equal to $1/k$. In terms of linear control theory, the system may be modeled as an integrator with a unity-gain feedback path, as shown in Fig. 4. The closed-loop transfer function is, therefore, given by

$$G_{CL}(s) = \frac{k}{s + k} \quad (2)$$

which shows that the loop's dynamics are only dependent on loop gain k . The main assumption made is that the magnitude of the input vector is within the synthesizable range of the system, i.e., $2R$ V. This is a fundamental condition for any LINC-like system with two component arms. If the magnitude is outside this range, then lock can never be established. The level of loop gain within the system also determines the maximum frequency component to which the system can lock. This value, f_{\max} , is also dependent on the instantaneous envelope level r and is given by

$$f_{\max} = \pm \frac{k}{2\pi r} \sqrt{4R^2 - r^2}. \quad (3)$$

The CALLUM1 system can be simplified to remove the requirement for a DSP or LUT. If the denominator terms of (1) are ignored, then a version known as CALLUM2 results. This is also stable, but unlike CALLUM1, its tracking performance

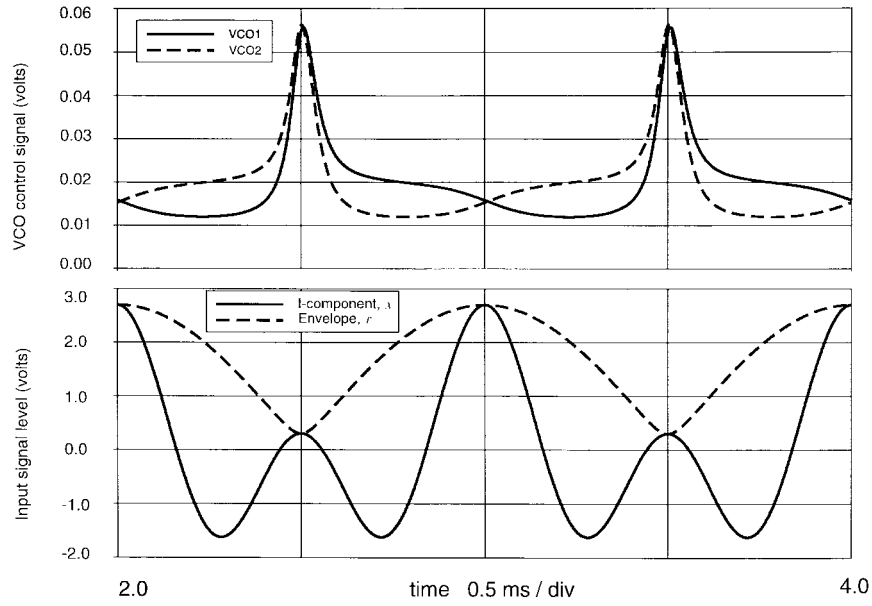


Fig. 3. Typical VCO control signals for a two-tone test. The tone amplitudes are unequal to ensure that the envelope does not fall to zero. $R = 1.5$ V, $k = 100\,000$.

degrades as the envelope of the input signal reduces. This is because loop gain (which directly affects tracking performance) is effectively reduced when the envelope becomes small. The linear model of CALLUM2 is similar to that of CALLUM1, except that the time-constant becomes envelope dependent and is given by $1/kr^2$. The maximum locking frequency is similar, but the r term occurs in the numerator rather than the denominator, thus

$$f_{\max} = \pm \frac{kr}{2\pi} \sqrt{4R^2 - r^2}. \quad (4)$$

Comparison of (3) and (4) shows that $f_{\max} \rightarrow 0$ as $r \rightarrow 0$ in the case of CALLUM2, whereas for CALLUM1, $f_{\max} \rightarrow \infty$ as $r \rightarrow 0$. This highlights CALLUM2's poor tracking performance at low envelope levels.

III. NONLINEAR CHARACTERISTICS

The behavior of CALLUM systems can be described by a set of nonlinear first-order differential equations. When the system is tracking, a linearized model can be used when considering small changes of either phase or amplitude of the input vector. When large changes in phase and amplitude occur or when the process of acquisition is occurring, the system's behavior can only be described by its governing set of nonlinear differential equations. In most cases, such equations cannot be solved analytically, thus, numerical methods must be used (e.g., Euler method or Runge-Kutta [11]). Graphical phase-plane techniques can be employed to provide a qualitative analysis and to provide insight into the nature of the solutions. Such an analysis will now be applied to the CALLUM1 system.

A. Solution Curves and Equilibrium Points

By considering the VCO control equation for CALLUM1 (1), a set of system equations can be derived by making use of

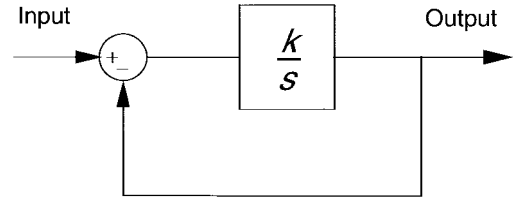


Fig. 4. Unity-feedback linear model of CALLUM1 for small changes in amplitude or phase. This model only applies once the system has acquired the input vector and lock has been established.

several geometric relations, which exist in Fig. 1 as follows:

$$\begin{aligned} \frac{d\theta_1}{dt} &= 2kgrR \cos\left(\frac{\theta_1 - \theta_2}{2}\right) \cos\left(\phi - \left(\frac{\theta_1 + \theta_2}{2}\right) - \beta\right) \\ &\quad - kgr^2 \cos \beta \\ \frac{d\theta_2}{dt} &= -2kgrR \cos\left(\frac{\theta_1 - \theta_2}{2}\right) \cos\left(\phi - \left(\frac{\theta_1 + \theta_2}{2}\right) - \beta\right) \\ &\quad + kgr^2 \cos \beta \end{aligned} \quad (5)$$

where

$$g = \sqrt{\frac{1}{r^2(4R^2 - r^2)} + \frac{1}{r^4}} \quad (6)$$

and

$$\tan \beta = \frac{\sqrt{4R^2 - r^2}}{r}. \quad (7)$$

The loop gain, k and the VCO magnitude R can be considered to be constant. When the input vector is of fixed magnitude and phase (i.e., DC conditions), the only time-varying parameters are the respective phases of each component vector θ_1 and θ_2 . In this case, the system of nonlinear equations can be solved by using numeric methods and a solution curve can be obtained for any arbitrary initial values of θ_1 and θ_2 . A set of curves can be plotted to obtain a phase portrait on the

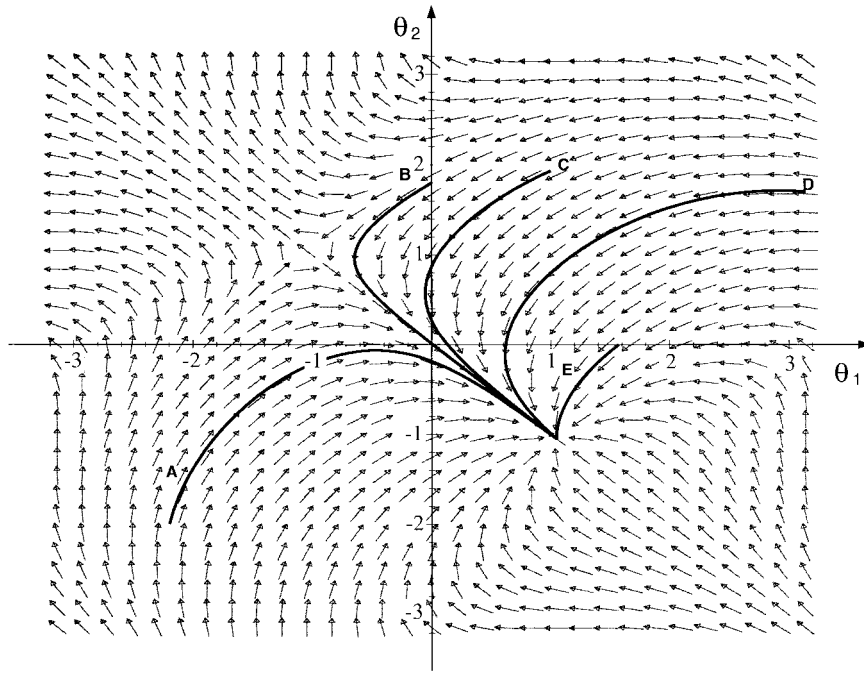


Fig. 5. Direction field and phase portrait showing five solution curves (A–E). The saddle point (second quadrant) and stable node (fourth quadrant) are clearly defined.

θ_1 versus θ_2 plane. A direction field, indicating the trajectory of solutions, can also be plotted by evaluating $d\theta_1/dt$ and $d\theta_2/dt$ over a grid of points in the same plane. At each point, a small arrow can be drawn to indicate the slope of the field at that particular point. Using a mathematical package such as Maple,¹ the phase portrait can readily be found. Fig. 5 shows the phase portrait and direction field for the case where the input vector is ($r = 1, \phi = 0$). The constants R and k are both unity. The five solution curves correspond with five initial starting positions of the two component vectors. All the solutions converge to a distinct point in the fourth quadrant. This point is known as an equilibrium point and corresponds to the condition

$$\frac{d\theta_1}{dt} = \frac{d\theta_2}{dt} = 0. \quad (8)$$

This equilibrium point can be classified as a stable node and corresponds to $\theta_1 = \pi/3, \theta_2 = -\pi/3$. This can be shown to synthesize the desired output. An equilibrium point also exists in the second quadrant, and also satisfies the condition of (8). In this case, the equilibrium point is unstable and is called a saddle point. Solutions can initially be attracted toward this point, but ultimately converge at the stable node. Compared to the case of the stable node, the positions of the two component vectors are exchanged; both of these equilibrium points will synthesize the desired output vector, but only one provides a stable solution. The direction field shows useful qualitative information about the nature of the system's solutions. The trajectory of the solution for any arbitrary set of initial conditions can easily be seen without having to calculate the actual solution curves. It is important to note that the direction field changes as the input vector

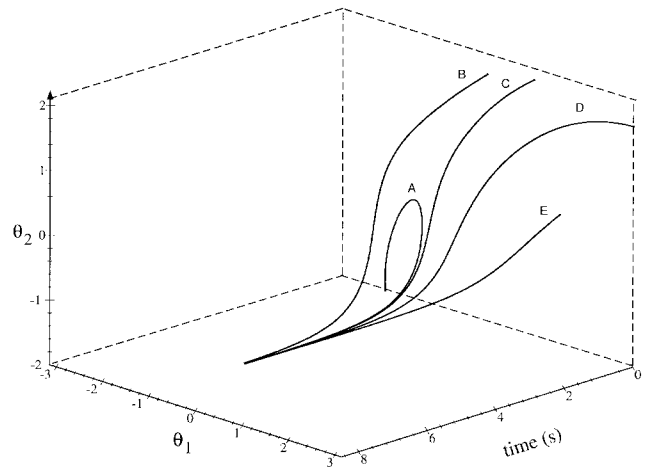


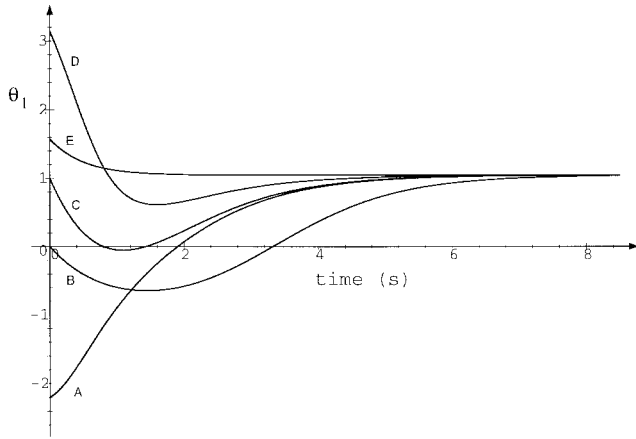
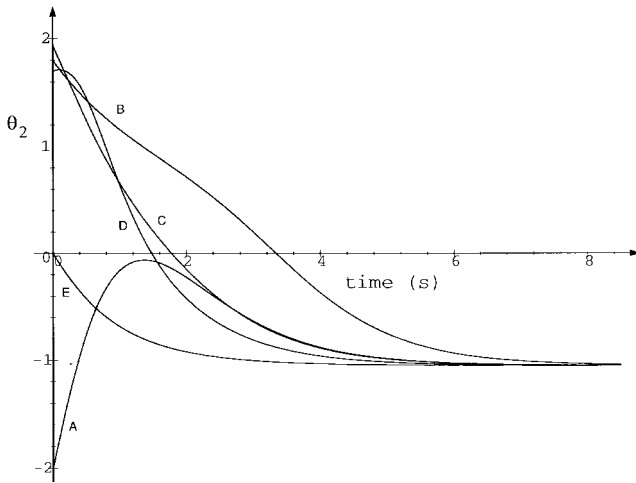
Fig. 6. Three-dimensional version of the phase portrait shown in Fig. 5, with time as the additional dimension.

changes. Nonlinear differential equations often have multiple equilibrium points (two are shown in Fig. 5), but an infinite number of periodic solutions exist due to phase wrapping. The direction field shows some solutions which leave the domain of the plane shown in Fig. 5; these solutions converge at one of the periodic solutions in an adjacent solution space; which are identical to the fundamental solution space shown in Fig. 5.

B. Acquisition

The phase portrait and direction field provides information on the nature of the solutions and can describe the trajectory of the solutions during the acquisition process. However, such plots do not convey any time information. This can easily be obtained by adding a third dimension, orthogonal to θ_1 and θ_2 , representing time. Fig. 6 shows such a plot for the same

¹Maple V Mathematics Package, Waterloo Maple Inc., Waterloo, Ont., Canada.

Fig. 7. Solution curves of Fig. 5 plotted on the $\theta_1 vt$ plane.Fig. 8. Solution curves of Fig. 5 plotted on the $\theta_2 vt$ plane.

example as used above. All the trajectories start at $t = 0$ and ultimately converge to the stable equilibrium position as $t \rightarrow \infty$. The convergence time is variable and is dependent on the particular solution curve taken. The three-dimensional plot assists in visualizing the system, but more useful information can be gleaned by plotting $\theta_1 vt$ and $\theta_2 vt$, as shown in Figs. 7 and 8. The nonlinear nature of the acquisition process is clearly shown. As in many nonlinear systems, small variations in the initial conditions can give rise to large variations in behavior. As expected, θ_1 converges to $\pi/3$ and θ_2 to $-\pi/3$ as $t \rightarrow \infty$. Fig. 9 shows the acquisition behavior of the I-component (x) for the same two-tone test as used in Fig. 3. Lock is achieved in approximately $50 \mu\text{s}$; from this point onwards, a finite steady-state error exists between the input signal and synthesized output. Both lock-time and steady-state error are reduced with increasing loop gain k . In this example, k was set at a low value to emphasize the steady-state error.

IV. HARDWARE IMPLEMENTATION OF CALLUM2

The CALLUM2 system can be implemented entirely in the analog domain, as the two VCO control signals can be generated easily using standard “linear” components. A hardware prototype of such a system has been constructed and

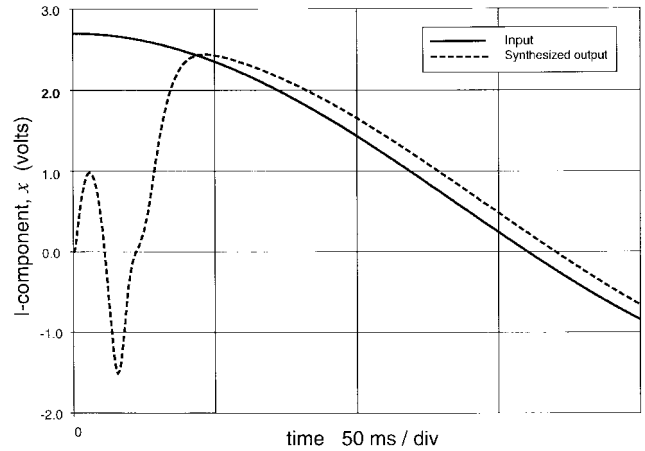


Fig. 9. I-component of the input and output vectors during and after the acquisition process.

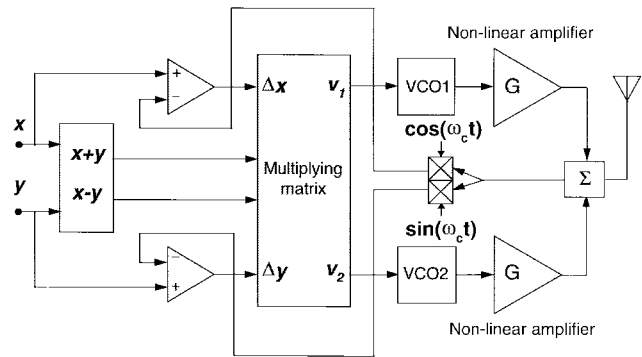


Fig. 10. Architecture of the CALLUM2 system.

tested in response to a typical complex modulating signal. The details of its construction and performance are given below.

A. Implementation Issues

The structure of CALLUM2 is shown in Fig. 10. The system was designed to operate at 220–240 MHz, although the choice of center frequency is arbitrary and has no effect on the baseband signal-processing design. The core signal-processing block is the multiplying matrix, which was implemented using four analog devices AD-835 wide-band multipliers. The error signal is generated using analog devices AD-830 differential amplifiers, as are the terms $x + y$ and $x - y$. The AD-830 can also be configured for resistorless summation. The $x + y$ term can be inverted to generate $-x - y$, as the AD-835 has differential inputs. The RF section includes the VCO's, nonlinear PA's, power combiner, and downconverter, as described below.

1) *Power Modules:* The PA's are Mitsubishi FM modules, which operate at approximately 45% efficiency with a gain of 36 dB (maximum output power = 7 W).

2) *Power Combiner:* Wilkinson-type—constructed using two quarter-wavelength 75- Ω coaxial cables lengths (ideally, this should be 70.7 Ω) with a 100- Ω load resistor. The resistor must be adequate to dissipate all the power from the two PA's; when the synthesized envelope is very small, the component signals sum while approaching antiphase and the unwanted

power must be dissipated in this load resistor. The power-combining process is problematic: the power loss increases as the phase angle between each RF component signal increases, ultimately dissipating all the power in the 100- Ω load resistor, when the signals are in antiphase. A solution to this problem might be to use a summing-switching amplifier arrangement or a voltage summation method. It may be possible to use an RF operational amplifier if only modest output power is required. If the dynamic range of the envelope of the modulating baseband signal is restricted so that it does not become too low, then the power loss in the combiner becomes less problematic. Due to the benefits of such a restriction, modulation schemes such as $\pi/4$ -DQPSK are ideal for use with CALLUM transmitters.

3) *Downconverter*: Two mini-circuits TUF-1 mixers are used to effect direct quadrature downconversion. The local oscillator (LO) is split into quadrature components by using a mini-circuits PSCQ-2-250 quadrature splitter. The intermediate-frequency (IF) output (in this case, baseband), is then amplified using operational amplifiers. These amplifiers have variable gain and a DC-offset adjustment so that any quadrature gain or phase imbalance can be compensated for.

4) *VCO*: This is a critical element of the CALLUM system. At first, the VCO's were implemented by using the DC-FM facility of two RF signal sources. The limited modulation port bandwidth of these sources (approximately 100 kHz at the -3 -dB point) resulted in a low-frequency pole in the feedback loop and caused instability at modest loop-gain levels. The onset of oscillation was signaled by an increase in the noise skirt at ± 90 kHz from the center frequency. To improve the bandwidth of the system and to allow the use of more loop-gain, the signal sources were replaced by 930-MHz VCO's (Z-Comm.). The outputs of the VCO's are divided by a factor of four by using prescalers (Motorola), which decreased the tuning sensitivity from 8 to 2 MHz/V and also improved phase noise performance. The sensitivity of the VCO's directly affects loop gain; 2 MHz/V is equivalent to a loop gain element of 2×10^6 , which is toward the upper limit for stable operation for this particular hardware system. To set the free-running frequency and to allow a bipolar control voltage, the VCO's were biased by summing in a DC level. During setup, this level was adjusted so as to have a free-running frequency equal to that of the intended LO. Unlike in many other VCO applications, it is essential to DC couple the VCO's to their respective control signals. The tuning-port bandwidth of these VCO's is in excess of 50 MHz and, thus, does not limit system stability, as delay or other system poles are more likely to be dominant. To prevent undesired loading effects, the output of each VCO is adequately buffered by a series attenuator followed by a monolithic-microwave integrated-circuit (MMIC) amplifier stage. The overall output power of the complete VCO blocks (including prescaler) is -6 dBm; added to the gain of the PA modules, this means that the average power output of each VCO/PA chain is 30 dBm (1 W).

A possible source for low-frequency poles are the operational amplifier stages in the downconverter. Devices with high gain-bandwidth product were used so that the bandwidth of the system could be made as large as possible. Loop gains 20 times

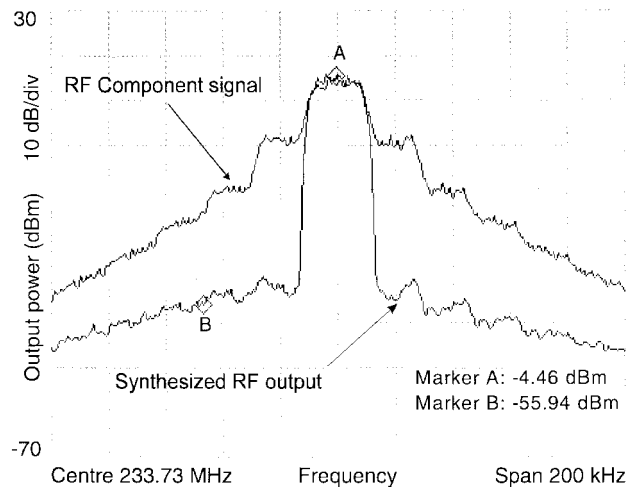


Fig. 11. Practical results at 233 MHz: synthesized output spectrum and component spectrum in response to a TETRA baseband modulating signal.

greater than those that could be used in the previous RF-signal source-based system could now be used before oscillation at ± 3 MHz ensued.

The entire system is locked to the LO reference, thus, changing the transmit channel simply consists of changing the LO frequency to the new channel. The new channel must, however, be well within the linearization bandwidth of the system. For example, if a 1-kHz tone was being transmitted, the tone would appear at $f_c + 1$ kHz. If the LO was changed to $f_c + 10$ kHz, then the system would be effectively attempting to track a tone of 11 kHz, which would demand more loop gain for the same tracking performance. If the VCO free-running frequency was also changed to the new channel frequency, the system would revert to tracking a 1-kHz tone and have the associated benefit of better tracking performance.

B. Results

After initial powering-up of the system, several parameters must be optimized before the desired operation is achieved. The most important tasks are to align the IQ demodulator (to minimize gain and phase imbalances) and to adjust the DC offsets around the loop (especially those which set the VCO free-running frequency). With the loop parameters set, modulation can be applied and any additional tuning can be performed if necessary. Although any baseband modulating signal can be applied to the system, it is advantageous to avoid signals in which the envelope falls to or approaches zero. This precludes the two-tone test as a meaningful measure of the modulator's performance. Instead, the system was excited by a $\pi/4$ -DQPSK signal compatible with the requirements of the terrestrial trunked radio (TETRA) ETSI standard, which specifies that the data rate should be 18 kbd with a filter alpha of 0.35 [12]. The nature of the signal prevents zero or low-envelope conditions, making it favorable for use with CALLUM. In response to such a signal, CALLUM2 produces an output spectrum as shown in Fig. 11. This figure also shows the power spectrum of one of the two wide-band phase-modulated component signals; the other component signal is the same, except for phase relationship. When these signals are

summed, frequency components outside the complex modulation bandwidth combine in antiphase and cancel, leaving the desired linearly amplified output. CALLUM2 cannot exhibit perfect cancellation, as it is an approximation of the ideal system (CALLUM1). Results show that linearity is good enough to achieve the transmission masks for most modulation formats including TETRA, as long as adequate stable loop gain can be provided.

V. SUMMARY AND CONCLUSIONS

In the CALLUM system, highly efficient switching-type nonlinear RF PA's can be used to generate a linear output. The potential of very high power efficiency from these systems makes them particularly suited to battery-operated mobile applications. Overall system efficiency is, however, limited by current power-combining methods. Due to its closed-loop nature, CALLUM is particularly suited to narrow-band systems such as TETRA. The optimal CALLUM1 system requires nonlinear calculations to be performed to obtain the ideal VCO control voltages. If these nonlinear operations are ignored, a simplified system known as CALLUM2 results. This version can be implemented using simple analog components, but suffers from poor tracking performance at low envelope levels, due to the dependence of loop gain on envelope level. If the envelope of the modulation signal does not vary over a wide range (as is the case with $\pi/4$ -DQPSK) then CALLUM2 can be particularly effective. The optimal CALLUM1 system has constant loop gain over the entire permissible envelope range and is, therefore, capable of tracking input signals in which the envelope drops to very low values. If the envelope falls to zero, as is the case in a standard two-tone test, then a discontinuity will occur, resulting in wide-band distortion products. This applies to all LINC systems other than those which use more than one component signal.

VI. FURTHER WORK

To fulfill the potential of the CALLUM technology, a power-efficient combining method is currently being sought. The optimal CALLUM1 system is under development by the authors and should give improved linearity, particularly with input signals having large envelope variations.

ACKNOWLEDGMENT

The authors would like to thank A. R. Champneys, K. Y. Chan, R. J. Wilkinson, and N. Vaughan for their assistance throughout this work.

REFERENCES

- [1] P. B. Kenington and A. Bateman, "RF linear amplifier design," in *Proc. RF Expo West*, Mar. 1994, pp. 223–232.
- [2] D. C. Cox, "Linear amplification with nonlinear components," *IEEE Trans. Commun.*, vol. COM-22, pp. 1942–1945, Dec. 1974.
- [3] F. Casadevall and J. J. Olmos, "On the behavior of the LINC transmitter," in *Proc. 40th IEEE Veh. Technol. Conf.*, May 1990, pp. 29–34.
- [4] M. K. DaSilva, "Vector-locked loop," U.S. Patent 5 105 168, Apr. 1992.
- [5] A. Bateman, "The combined analogue locked loop universal modulator (CALLUM)," in *Proc. 42nd IEEE Veh. Technol. Conf.*, May 1992, pp. 759–763.
- [6] K. Y. Chan and A. Bateman, "Analytical and measured performance of the combined analogue locked loop universal modulator (CALLUM)," in *Proc. Inst. Elect. Eng. Commun.*, vol. 142, no. 5, Oct. 1995, pp. 297–306.
- [7] ———, "Linear modulators based on RF synthesis: Realization and analysis," *IEEE Trans. Circuits Syst. I*, vol. 42, pp. 321–333, June 1995.
- [8] D. J. Jennings and J. P. McGeehan, "Hardware implementation of optimal CALLUM transmitter," *Electron. Lett.*, vol. 34, no. 19, pp. 1816–1817, Sept. 1998.
- [9] F. M. Gardner, *Phaselock Techniques*, 2nd ed. New York: Wiley, 1979.
- [10] K. Y. Chan and A. Bateman, "Analysis and topologies for high efficiency amplifiers based on RF synthesis," in *Proc. Inst. Elect. Eng. Conf. Radio Receivers Assoc. Syst.*, no. 415, Sept. 1995, pp. 212–217.
- [11] S. D. Conte and C. deBoor, *Elementary Numerical Analysis: An Algorithmic Approach*, 3rd ed. New York: McGraw-Hill, 1980.
- [12] ETSI Draft TETRA Standard, Document Draft pr ETS 300 392-2:1994, 1994.



David J. Jennings received the B.Eng. degree and the M.Sc. degree in communication systems and signal processing from the University of Bristol, Bristol, U.K., in 1991 and 1995, respectively, and is currently working toward the Ph.D. degree in linear RF amplifiers at the Centre for Communications Research, University of Bristol.



Joseph P. McGeehan received the B.Eng. and Ph.D. degrees in electrical and electronic engineering from the University of Liverpool, Liverpool, U.K., in 1967 and 1971, respectively.

In 1970, he was appointed Senior Scientist at the Allan Clark Research Centre, Plessey Company Ltd., where he was responsible for the research and development of two- and three-terminal Gunn effect devices and their application to high-speed logic, telecommunications, and radar systems. In 1972, he became an Academic Staff Member of the School of Electrical Engineering, University of Bath, and initiated research in subsequently linear modulation (SSB) for mobile radio. In 1984, he was appointed to the Chair of Communications Engineering at the University of Bristol, Bristol, U.K., and is currently Dean of the Faculty of Engineering and Director of the University Research Centre in Communications Engineering.

Dr. McGeehan is a fellow of the Institution of Electrical Engineers (IEE), U.K., the Royal Academy of Engineering, and the Royal Society of Arts and Commerce. He serves on numerous national and international committees concerned with mobile communications. He was the recipient of the IEEE Neal Shephard Award for a paper published on adaptive beamforming techniques for cellular radio, and was co-recipient of the IEE U.K., Proceedings Mountbatten Premium Award for papers published on satellite systems. He has also received awards from the Motorola Research Foundation (US) and Schlumberger Industries (France) for his research contributions to radio communications.